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THE ISODOSE LINE FIELD OF COSMIC RAY HEAVY NUCLEI TRACKS IN TIS--ETC(U)
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THE ISODOSE LINE FIELD OF COSMIC RAY
HEAVY NUCLEI TRACKS IN TISSUE

Hermann J. Schaefer

Office of Naval Research
Contract #N00014-76-C-0544
Final Report

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SUMMARY

THE PROBLEM

Recent theoretical and experimental studies have greatly enhanced the knowledge of track structure of heavy ions. Aerospace medicine benefits from this progress by gaining a better understanding of the health hazard to astronauts from cosmic ray heavy primaries (so-called HZE particles) in space. From the dosimetric viewpoint, interest centers on the problem of quantitatively separating that part of the total dose from heavy primaries which acts on tissue essentially in the same way as conventional nuclear radiations from the complementary part which, by virtue of its extremely high local energy density (ED) values, has been shown to produce micro-lesions in tissue for single events.

FINDINGS

Detailed charts showing the isodose line field of an Fe track in tissue at different resolutions demonstrate the three different levels of ED: the peripheral region of the penumbra where the radiation field closely resembles an x or gamma ray field, the core region for medium and high energies of the primary where ED is quite similar to an ordinary alpha particle, and the core region for low energy in the terminal section of the track where ED greatly exceeds all levels known for conventional kinds of densely ionizing particles. Evaluated in terms of absorbed dose, the third part constitutes only a very small fraction of the total from all three components. Although not well understood yet in its mode of action on living tissue, the third fraction appears now defined more accurately at least in its physical characteristics. For operational personnel dosimetry, one has to satisfy oneself for the time being with record keeping of the physical parameters. As research progresses, it will eventually be possible to interpret such records in terms of dose equivalents.

INTRODUCTION

The basic concepts underlying the dosimetry of conventional ionizing radiations find their expression in the definitions of the rad and rem unit and Linear Energy Transfer (LET) and Quality Factor (QF). Their application to the dosimetry of heavy ions runs into difficulties. The LET concept in particular is inadequate because it does not discriminate particles with the same LET yet different diameters of their tracks. On the other hand, LET is a fundamental magnitude for the dosimetry of any nuclear radiation because it determines the QF, i.e., the conversion factor from absorbed dose (rad) to the dose equivalent (rem).

In a preceding report, hereafter referred to as Report 1, the concept of the energy density (ED) distribution of a mixed beam of heavy nuclei has been introduced as counterpart to the LET distribution for conventional nuclear radiations. The report presents LET distributions for two representative HZE particle beams as they follow from theory as reviewed by Chatterjee and Schaefer (2) earlier. The computational methods for such numerical evaluations are somewhat involved. However, the radiobiological significance of the ED distribution can be understood easily in non-mathematical language with the aid of explicit graphical plots of the microdosimetric radiation field of a heavy particle track in tissue. Such plots are of special value if the radiobiologist wants to visualize the topological details in the micro- and ultrastructure of cellular tissue traversed by a heavy particle. This report supplements Report 1 (1) by presenting such explicit isodose line charts for the beams analyzed earlier.

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BASIC CONCEPTS

The theory of track structure distinguishes two regions: core and penumbra. The core is a narrow central zone with a radius well below 1 micron in water or tissue where energy deposition occurs mainly in processes of excitation and electron plasma oscillation.

The penumbra is a peripheral zone enveloping the core where energy is dissipated mainly in ionizations produced by secondary electrons released in the center of the core yet traveling in tortuous trajectories. The distinction between core and penumbra is an artificial concept mainly for conducting the analytical process. Actually, there is no well defined border separating the two different processes of energy dissipation. At the present state of knowledge, the radial structure of a heavy ion track can be analyzed in quantitative terms only for the penumbra. For the core, merely the total energy dissipation unresolved as to its radial profile can be determined.

In the penumbra, ED decreases with the square of the radial distance from the center of the track. The maximum distance to which the penumbra extends depends on the maximum transferable energy to electrons which in turn depends on the instantaneous speed of the primary particle. It is self-evident that, in the outermost periphery of the penumbra, energy is deposited mainly by terminating electrons. Since their LET is comparatively high and the local ED small because of the low fluence large statistical fluctuations of the local dose occur on the cellular level.

Visualizing a tissue cube of 3×10 micron size as target, one calculates easily that a local dose of 1 rad requires only three electrons terminating in the target. According to the laws of statistics, the individual frequencies of independent events in a population of targets receiving a mean frequency of three events per target obey a Poisson distribution. Converting events, i.e., terminating electrons to doses, we learn from Poisson's Law that about half the population of targets will receive doses between 0.5 and 1.5 rad whereas the remainder receives either smaller doses down to zero or larger ones up to 2.5 rad or (less than 1 per cent) even 3 rad and more. As we select mean doses still smaller than 1 rad, the fluctuations rapidly assume proportions which make the concept of a mean cellular dose meaningless from the radiobiological viewpoint. At the same time, the energy dissipation pattern in the track region in question resembles the one found in a field of x or gamma rays. A detailed analysis of this particular pattern, then,

appears of no interest in a study exploring the specifically new and different characteristics of heavy ion tracks.

Figure 1 demonstrates the quantitative aspects of the just explained relationships for the terminal section of 1.8 cm length of an Fe track ($Z = 26$) in tissue. Read with the left-hand ordinate scale, the curve shows the radial extension of the track as it follows from theory (2). However, consulting the right-hand ordinate scale one realizes that the large radial extension of the track does not at all coincide with the region where high ED values prevail. In fact, it appears that the terminator, i.e., the maximum radius of the track, is largely an academical concept. The very small ED values prevailing locally at the terminator indicate that it does not represent a continuous borderline but merely denotes the maximum distance to which an occasional electron carrying the maximum transferable energy might travel.

High and very high ED values constituting the unique characteristic of heavy ion tracks are limited to the core and a narrow region of the penumbra directly adjacent to the core. The resolution of the ordinate scale in Figure 1 is much too coarse to indicate that region. As we proceed to examine it more closely, the question arises what specific ED value should be selected as the threshold setting apart high and very high ED values in the just indicated sense. One is immediately reminded of the corresponding problem in conventional dosimetry where the LET of 3.5 kev/micron tissue is officially designated as the limit separating the normal region ($QF = 1$, rem = rad) from the abnormal one ($QF > 1$, rem > rad). If an ED limit could be defined in a similar way for heavy ion beams it would allow the assessment of the fraction of the total absorbed dose for which new ways of determining the dose equivalent would have to be found and separate it from the remainder to which ordinary dosimetric concepts could be applied. Considering the enormous complexity of the response of living matter to ionizing radiation, one seriously doubts that a threshold ED of the indicated kind can ever be defined in a general way. Nevertheless, the concept of such a threshold has definite heuristic value. A further pursuit of these aspects is beyond the scope of this report which merely intends to

discuss the dosimetric ramifications of the problem. Familiarity with the pertinent relationships is a prerequisite for meaningful radiobiological experimentation.

THE ISODOSE LINE FIELD

The Z spectrum of galactic heavy primaries is usually presented in terms of particle fluences for Z groups rather than individual Z numbers. However, for establishing specific values of range, energy, dose, etc., the group fluence is assigned to a representative mean Z number. For the heaviest class ($Z \geq 20$), the preferred element is iron, Fe, $Z = 26$, because it shows the highest abundance in the class. Accordingly, we proceed to examine the isodose line field of an Fe track in tissue.

Figures 2, 3, and 4 show the field for three different range intervals covering the terminal section of 12 cm length. Special attention is directed to the fact that radial distance on the ordinate scale is expressed in two different units, millimicron (millimicrometer, μm , 10^{-7} cm) for the core and micron (micrometer, μm , 10^{-4} cm) for the penumbra. The transitional region where the penumbra changes over into the core is not indicated in the graph because resolution of the field in that particular region is beyond present knowledge as pointed out earlier. Within the penumbra, ED varies with the inverse square of radial distance from the center. Applying the law, one can easily establish any additional isodose lines down to the region close to the terminator of the core.

It might at least briefly be mentioned at this point that the isodose line field for an Fe track ($Z = 26$) shown in Figures 2 to 4 can be converted into the corresponding field for any other Z number by applying appropriate constant factors to the abscissa values and ED parameters while leaving the ordinate values unchanged. If we designate the Atomic Number of Fe by Z and the Atomic Weight by A, any range R of an Fe particle converts into the corresponding range R_N of any other element Z_N , A_N according to the relationship $R_N = R(Z^2 A_N)/(Z_N^2 A)$ if the energy per nucleon is to remain the same. The indicated transformation can be carried out in a straight-

forward way for all ranges of the Fe track down to about 1 millimeter in tissue. For shorter ranges, a correction is required because the effective Z determining the LET becomes increasingly smaller than the true Z when the nucleus begins to pick up orbital electrons. However, for all conceivable radiobiological applications the correction remains insignificant. A more systematic treatment of the method of unified field coordinates is not attempted at this time.

The specific advantage of portraying track structure by means of the isodose line field rests in the fact that the field can be projected directly on experimental systems containing biological specimens. Macroscopic shielding effects and depth dose distributions as well as microscopic target geometries can be examined easily with such superpositions. Quite generally, all physical parameters affecting a planned experiment can be brought out to any degree of accuracy provided the Z and E spectrum of the incident particle fluence is known. Interpreting the physical characteristics radiobiologically and determining the fractional fluence with ED levels basically different from those of conventional nuclear radiations is quite another problem.

How complex the latter issue really is becomes apparent if one compares tracks of heavy ions with those of ordinary alpha particles. Wingate and Baum (3) have measured radial ED profiles of alpha particles in tissue-equivalent gas at low pressure. Figure 5 shows their findings for a 3 Mev alpha particle with distances scaled down to the higher density of tissue. Also shown in the same graph is the ED profile of an Fe nucleus of 100 Mev/nucleon as it follows from the theory of track structure (2). The close resemblance of the two profiles is obvious. To be sure, the profiles do differ with regard to their radial extensions that cannot be indicated in Figure 5. While the Fe track extends to a radial distance of about 35 microns in tissue, the alpha track has a radius of only about 50 millimicrons or 500 Angstroms. Notwithstanding this difference, the essential point is the close similarity of the two tracks in their respective central regions where very high ED values prevail. Having examined Figure 5, one harbors serious doubts that the local

damage to subcellular entities in the cores of the two tracks should be greatly different. One can further conclude, then, that the conversion from absorbed doses to dose equivalents for an Fe track of 100 Mev/nucleon should be carried out in the same way as for an alpha particle of 3 Mev, i.e., by applying the same QF. Remembering that the energy spectrum of galactic radiation in space extends far beyond 100 Mev/nucleon with a broad maximum at 300 Mev/nucleon, we realize that the bulk of the fluence of heavy particles in space produces even smaller ED values in tissue than do 3 Mev alpha particles. Only the very small fluence of low-energy particles represents the unknown quantity which conventional dosimetry cannot adequately measure.

CONCLUSION

Summarizing the findings of the foregoing analysis, one can say that three different patterns of energy dissipation occur in the region field of a heavy ion track in tissue. Two of them are essentially identical with well known patterns of conventional radiations. One, prevailing in the more peripheral regions of the penumbra, closely resembles an x or gamma ray field and the other, prevailing in the core of a primary of medium or high energy, closely resembles the track of a low-energy alpha particle. Only the third pattern is new and different. It is limited to the core of the terminal section. Its radial extension remains in the dimension of ordinary alpha tracks yet the ED exceeds the level for alpha particles by several orders of magnitude. For galactic radiation in space, only a very small fraction of the total absorbed dose from heavy particles accrues from the third type. While present radiobiological knowledge is inadequate for quantitating the third fraction in terms of a unit similar to the rem for protons and alpha particles, at least the physical parameters such as event frequencies and distribution of track segment lengths can be determined. In fact, these parameters can be measured quite accurately with plastic foils and nuclear emulsions. As the study of biological effects of heavy particles progresses, it should eventually be possible to interpret recordings of the physical parameters in terms of "dose equivalents".

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1. Schaefer, H. J., Dosimetric Classification of Mixed Beams of Cosmic Ray Heavy Nuclei in Space. Faculty of Physics, University of West Florida, Pensacola, Florida 1976.
2. Chatterjee, A. and Schaefer, H. J., Microdosimetric Structure of Heavy Ion Tracks in Tissue. Rad. and Environm. Biophys. 13, 215-227, 1976.
3. Wingate, C. L. and Baum, J. W., Measured Radial Distribution of Dose and LET for Alpha and Proton Beams in Hydrogen and Tissue-equivalent Gas. Rad. Res. 65, 1-19, 1976.

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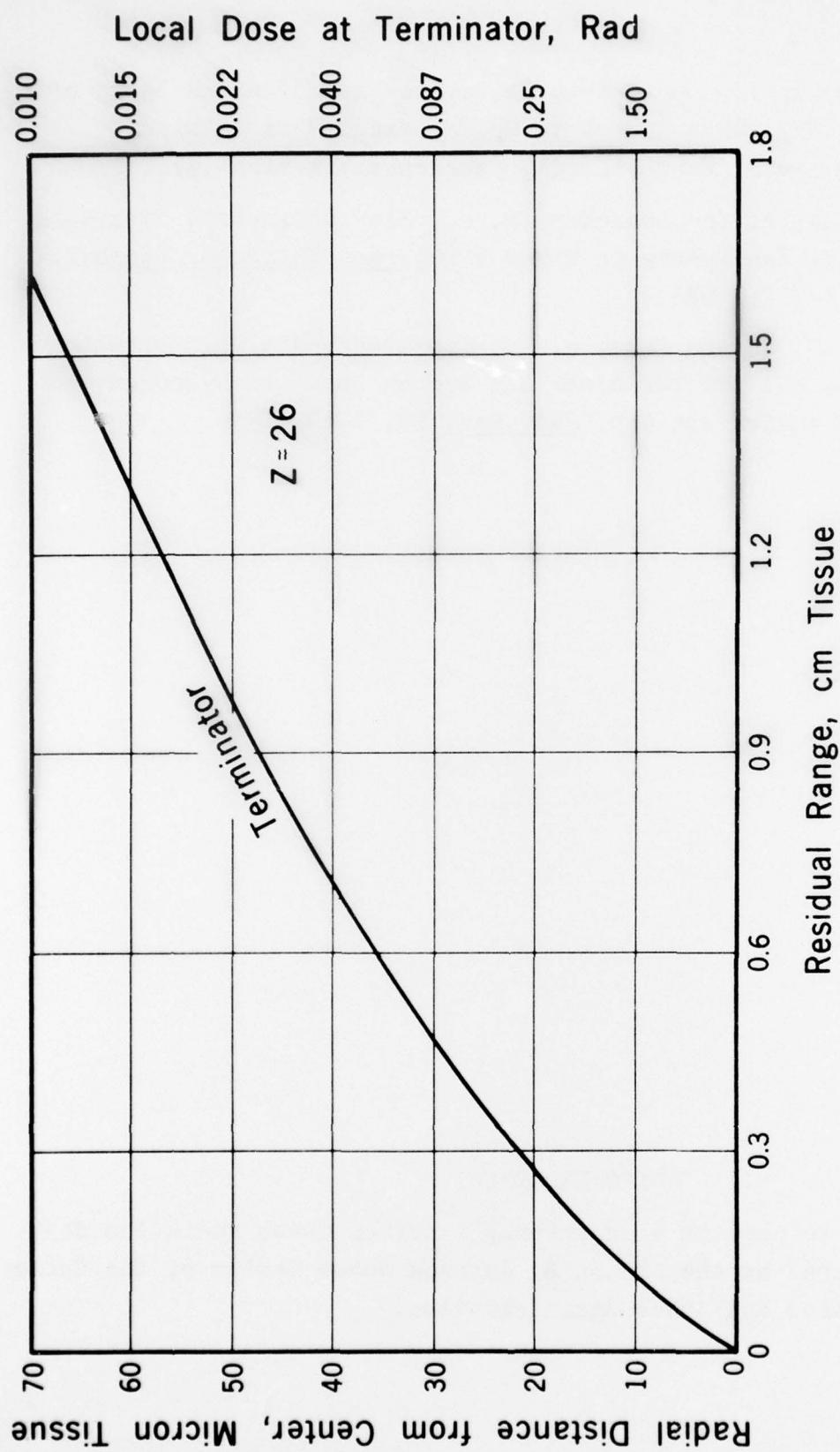


FIGURE 1
Radial Extension and Local Dose at Terminator
for Fe Track in Tissue

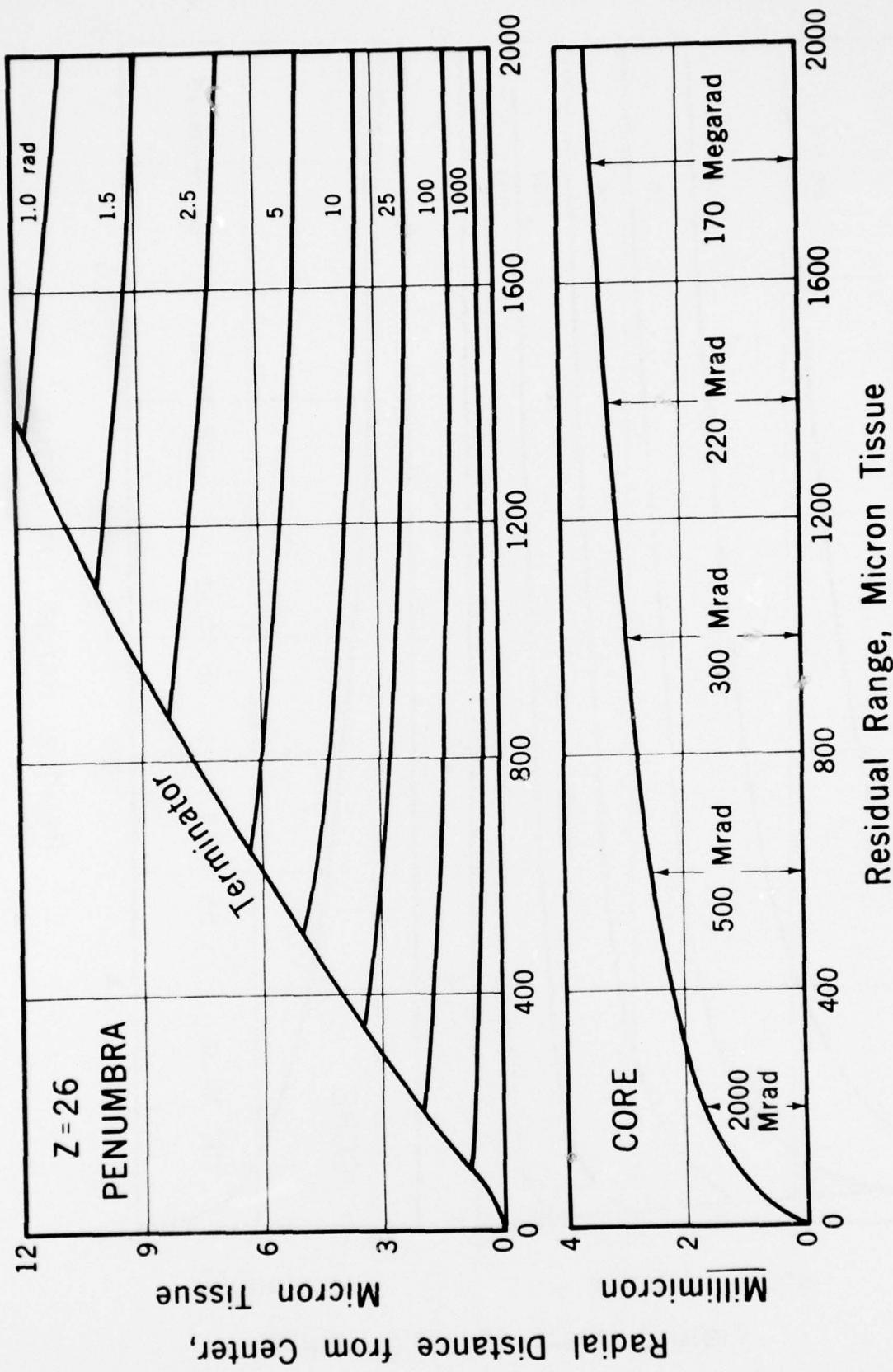


FIGURE 2. Isodose Line Field of Fe Track in Tissue. Range 0 - 2000 μ T.

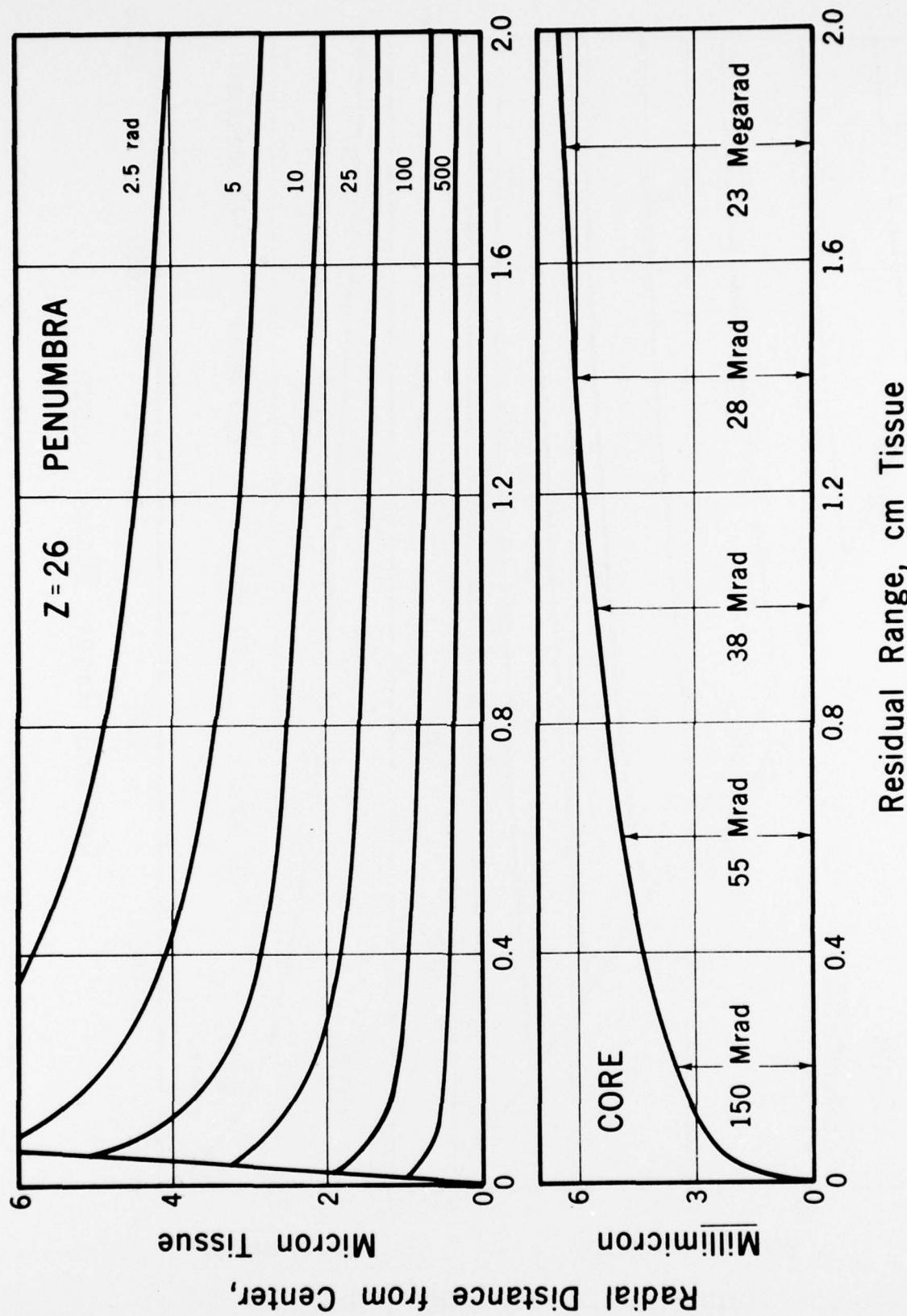


FIGURE 3. Isodose Line Field of Fe Track in Tissue. Range 0 - 2 cm T.

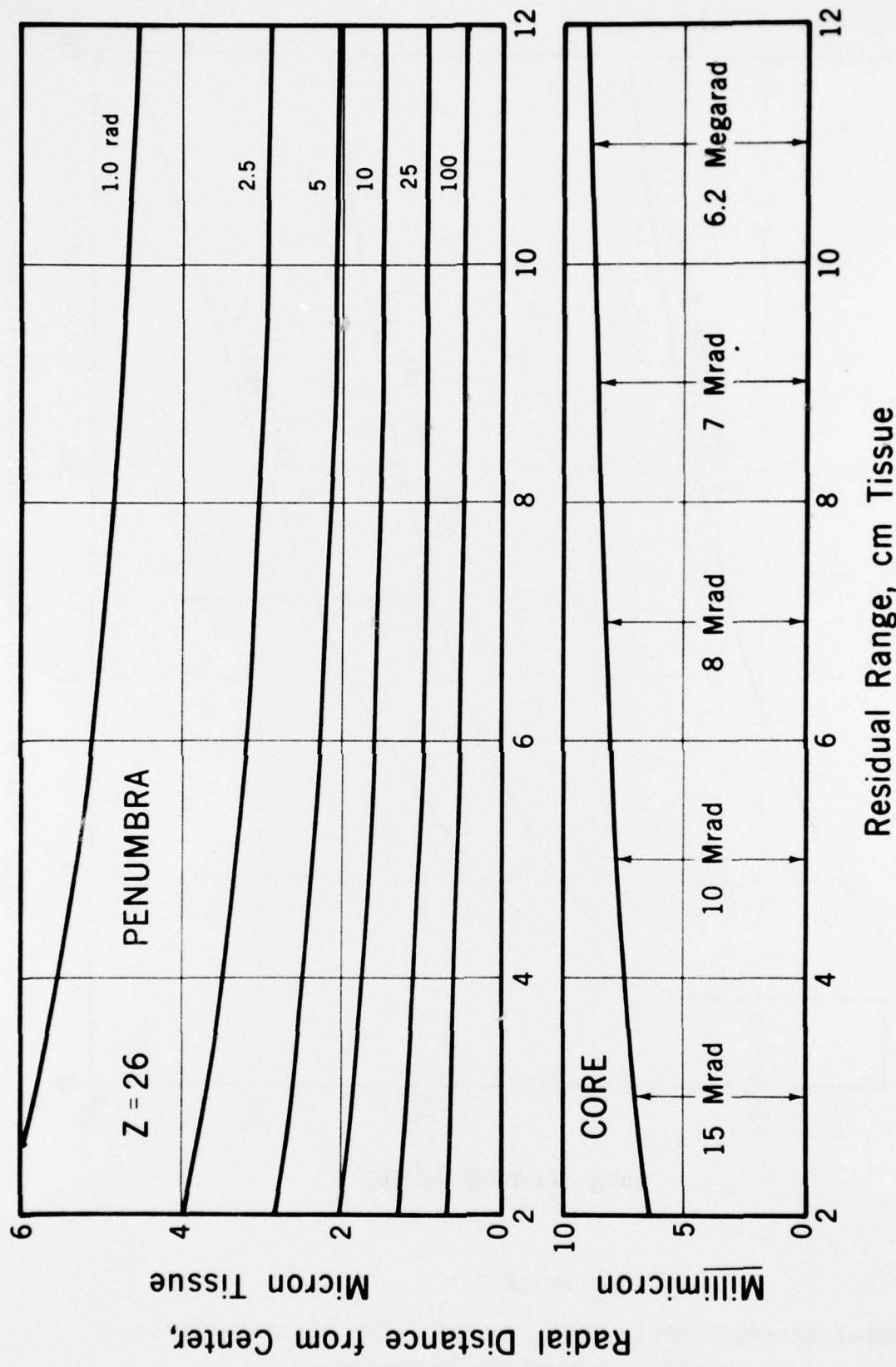


FIGURE 4. Isodose Line Field of Fe Track in Tissue. Range 2 - 12 cm T.

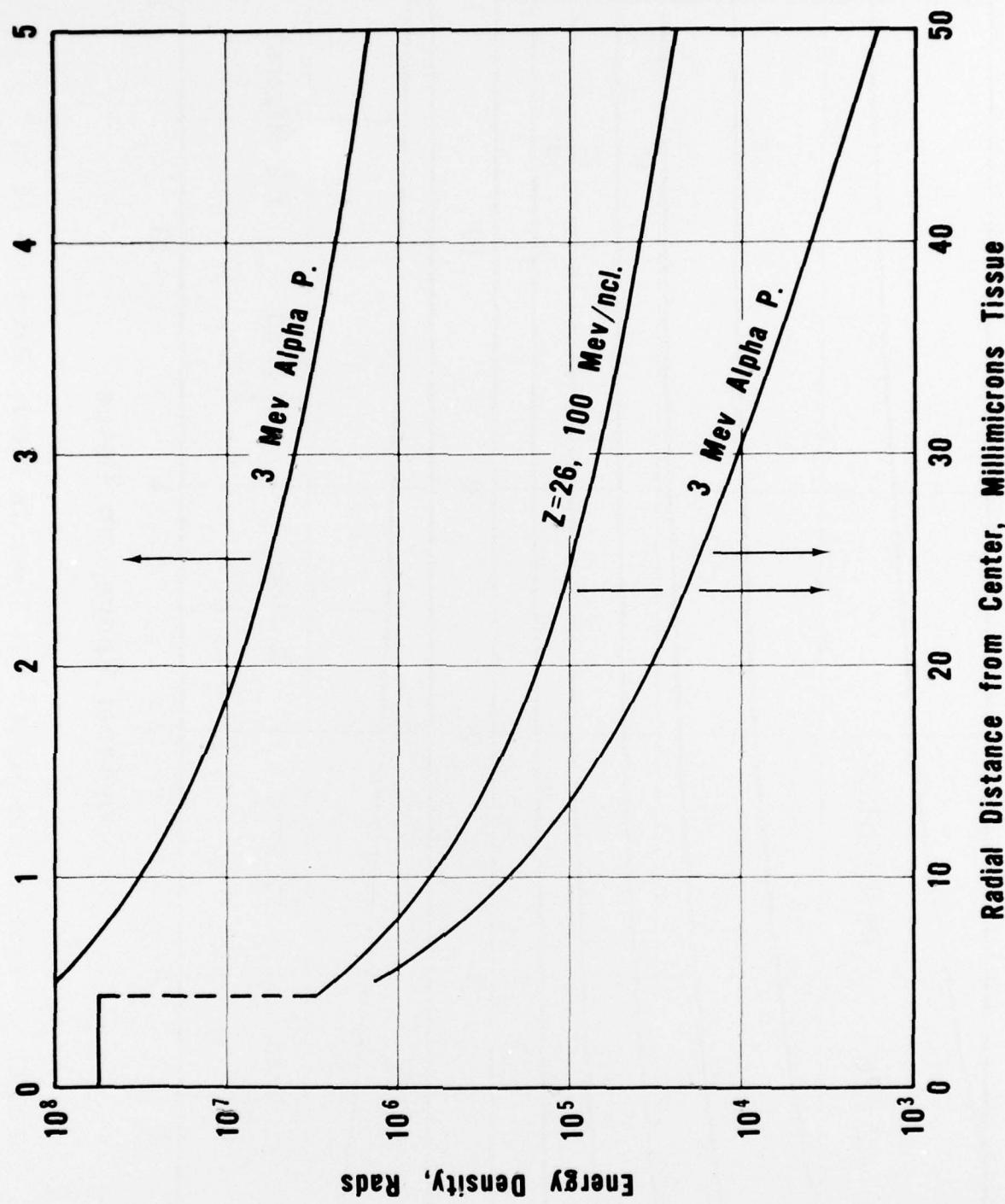


FIGURE 5
 Radial Energy Density Profiles for 3 Mev Alpha Particle
 and 100 Mev/nucleon Fe nucleus.

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In exhibiting local dose levels larger by several orders of magnitude. Since the mode of action of such "microbeam" hits on living matter is as yet incompletely understood, measuring exposure with a dosimetric unit similar to the rem is at present beyond reach. Therefore, record keeping on personnel exposures remains limited, for the time being, to the physical parameters. As radiobiological research with heavy ions progresses, it should eventually be possible to evaluate such records in terms of "dose equivalents".